Physics Letters B 679 (2009) 330–333

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Roles of one-step process on neutrino scattering off ^{12}C

K.S. Kim [a], Myung-Ki Cheoun [b,*]

[a] School of Liberal Arts and Science, Korea Aerospace University, Koyang 412-791, Republic of Korea
[b] Department of Physics, Soongsil University, Seoul 156-743, Republic of Korea

ARTICLE INFO

Article history:
Received 27 March 2009
Received in revised form 4 June 2009
Accepted 31 July 2009
Available online 11 August 2009
Editor: J.-P. Blaizot

PACS:
25.30Pt
23.40Bw
26.30.+k

ABSTRACT

Neutrino (ν) (antineutrino ($\bar{\nu}$)) scattering off ^{12}C in the energy range from a few to tens of MeV is one of key reactions for the ν-process in the nucleosynthesis of light nuclei, which usually assumes two-step process. Target nucleus is excited through various transitions by incident $\nu(\bar{\nu})$, and subsequently decay into other nuclei with emitting particles. However, one-step process is also feasible, in which incident $\nu(\bar{\nu})$ strips directly one nucleon from target nucleus. Consequently, the one-step process may affect abundances of ^{11}C and ^{11}B in addition to the two-step process. We investigate the one-step process in the $\nu(\bar{\nu})$ quasi-elastic scattering off ^{12}C with inclusion of the final state interaction between outgoing nucleon and residual nucleus, and evaluate effects of the one-step process in the relevant cross sections. The one-step process turned out to be comparable to the two-step process and the amount could be sensitive on the FSI.

1. Introduction

Neutrino (ν) (antineutrino ($\bar{\nu}$)) scattering with a complex nucleus plays important roles of studying ν oscillation parameters, such as mass hierarchy and mixing angle θ_{13}, as well as nuclear structure probed by weak interaction [1–4]. In particular, a lot of interests have been focused on the ν-process in the formation of a core collapsing supernova because cross sections for the neutrino(antineutrino)–nucleus ($\nu(\bar{\nu}) - A$) scattering are some of the most important input data for a network calculation estimating the abundances of light nuclei like ^{7}Li and ^{11}B. The abundance ratios turn out to be sensitive to the ν oscillation parameters [2]. Incident $\nu(\bar{\nu})$ energies exploited in these calculations [1,2] are focused on the energy range from a few to tens of MeV because relevant $\nu(\bar{\nu})$ energy spectra emitted from a proto-neutron star are presumed to be peaked mostly around the energy region. Not only the abundances of light nuclei but also the production of heavy nuclei such as ^{138}La and ^{180}Ta can be influenced by the ν-process [3].

Since the weak interaction is mediated by Z^0 and $W^\pm$ boson, there are two kinds of reactions, charge current (CC) and neutral current (NC) reactions. The two descriptions of ν–A scattering can be classified as two-step process and one-step process. For the two-step process, the incident $\nu(\bar{\nu})$ excites target nucleus, and then the excited target nucleus is subsequently decayed into other nuclei by emitting some particles incoherently,

Two-step process:

$$A\big(\nu(\bar{\nu}), \nu'(\bar{\nu}')\big)A^*, \quad A^* \to B + \text{outgoing particles: NC},$$
$$A\big(\nu_l(\bar{\nu}_l), l(\bar{l})\big)B^*, \quad B^* \to C + \text{outgoing particles: CC}. \tag{1}$$

The excitation occurs through various transitions i.e., super allowed Fermi ($J^\pi = 0^+$), allowed Gamow Teller ($J^\pi = 1^+$), spin dipole ($J^\pi = 0^-, 1^-, 2^-$), and other higher multipole transitions. Therefore dominant contributions of the two-step process stem from discrete and giant resonance (GR) states of the compound nucleus. Their typical excitation energies are below tens of MeV.

However the one-step process is also possible [5], in which a nucleon inside a target nucleus is directly stripped from the target nucleus without any excitation of target nucleus,

$$\text{One-step process:} \quad A\big(\nu(\bar{\nu}), \nu'(\bar{\nu}')N\big)B\text{: NC},$$
$$A\big(\nu_l(\bar{\nu}_l), l(\bar{l})N\big)C\text{: CC}. \tag{2}$$

The one-step process is the main reaction in the quasi-elastic (QE) peak region, where the incident $\nu(\bar{\nu})$ scatters off individual nucleons quasi-freely.

If the outgoing particle in the two-step process is a nucleon, both processes could not be distinguished because these two processes have identical final states. For example, $^{12}\text{C}(\nu, \nu')^{12}\text{C}^* \to {}^{11}\text{B} + p$ (or $^{11}\text{C} + n$) reaction via NC could not be distinguished from $^{12}\text{C}(\nu, \nu' p)^{11}\text{B}$ (or $^{12}\text{C}(\nu, \nu' n)^{11}\text{C}$). Similarly, $^{12}\text{C}(\nu_e, e^-)^{12}\text{N}^* \to {}^{11}\text{C} + p$ and $^{12}\text{C}(\bar{\nu}_e, e^+)^{12}\text{B}^* \to {}^{11}\text{B} + n$ reactions through CC also

* Corresponding author.
E-mail address: cheoun@ssu.ac.kr (M.-K. Cheoun).

0370-2693
doi:10.1016/j.physletb.2009.07.074

could not be differentiated from $^{12}\mathrm{C}(\nu_e, e^- p)^{11}\mathrm{C}$ and $^{12}\mathrm{C}(\bar{\nu}_e, e^+ n)^{11}\mathrm{B}$, respectively.

2. Motivation

The one- and two-step processes could influence the nuclear abundances in the network calculation initiated from ^{12}C by the ν-process [2]. Most of calculations are focused only on the two-step process. But some contributions of the one-step process could exist to the nuclear abundance because the incident ν emitted from the core collapsing supernova may have the energy high enough to excite continuum states above one nucleon emission threshold. The motivation of this work is to estimate contributions by the one-step process to the nuclear abundance.

In the experimental side, only a few data for the first stage of Eq. (1) which is the formation of compound nuclei have been reported as a flux averaged total cross sections since 1990. The data for inclusive reaction such as $^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$ show about $4.3 \sim 5.7$, while the data for exclusive reaction like $^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$ and $^{12}\mathrm{C}(\nu, \nu')^{12}\mathrm{C}$ (15.11 MeV) are restricted to $8.9 \sim 10.5$ and about 11 in the 10^{-42} cm^2 unit, respectively. All these data are measured from accelerated-based data.

Unfortunately, there are no data including the decay processes, which is the second stage in the two-step process. As for the one-step process like Eq. (2), there are no data because of various difficulties in the coincident detection of final ν and outgoing nucleon. Future ν factory for intense and mono-energetic $\nu(\bar{\nu})$ beam [6–9] could yield more fruitful data for the $\nu(\bar{\nu})$–A scattering.

To compare both one- and two-step processes, we briefly summarize recent theoretical status about the two-step process with detailed references. Many theoretical calculations [4,5,10–21] have been done for the experimental data on the excitation of the target nuclei ^{12}C since the pioneering work by Cornell et al. [10]. Conventional approaches for the ν–A scattering in the low energy region are shell model (SM) [4], random phase approximation (RPA) [11,16], and Quasi-particle RPA (QRPA) [5,11,12]. Detailed summary and comparison of the calculations are done in Refs. [11,19].

Although results of most SM calculations [4,11] converge more or less on the experimental data, they depend on the particle model space and the given Hamiltonian. But the RPA [11,16] and the QRPA [5,11,12], whose approaches satisfy the energy weighted sum rule [11], overestimated the data by a factor of $4 \sim 5$. In particular, recent calculation by proton-neutron QRPA [12] shows more improved results by simultaneously considering other relevant processes.

On the other hand, while most of SM, RPA and QRPA do not take explicitly the contribution from the QE region into account, the continuum RPA (CRPA) [13–24] includes continuum excitation spectrum beyond nucleon threshold in the QE region in addition to the discrete and GR states. The CRPA shows nearly identical results compared to other approaches for the ν–A scattering by the decay at rest (DAR) neutrino, so that the QE contribution seems to be small enough to be neglected in a few tens of MeV region. For the decay in flight (DIF) neutrino, it shows some deviations from other approaches beyond 150 MeV region. However, it might be quite difficult to separate contributions from the QE region in the CRPA. Our calculation can identify the QE contribution by calculating the one-step process. Of course, the $^{12}\mathrm{C}(\nu_\mu, \mu^-)^{12}\mathrm{N}$ anomaly, in which theoretical evaluation overestimates the experimental data, still remains to be solved.

Moreover, the application of the CRPA and other approaches to the ν reaction is restricted to the first stage of the two-step process. At the second stage, the excited nuclei subsequently decays into other nuclei with emitting particles such as proton, neutron, alpha, γ, and so on [2,4]. To describe this second stage, one needs additional calculation for the branching ratios into decay processes like Hauser–Feshbach (HF) statistical model [4,25]. Final state interactions (FSI) between outgoing nucleon and residual nuclei should be also taken into account at this stage. Actually, for the nuclear abundance, the two stages are successively considered in the two-step process.

In this work, we estimate the contributions of the one-step process and compare our results to those by the two-step process described by the SM for the first stage and the HF statistical theories for the second stage [2]. In order to calculate the one-step procedure we use the distorted wave Born approximation (DWBA) formalism which has been successfully applied to the QE electron scattering for a long time.

3. Formalism

Since the framework of the DWBA is focused on a nucleon inside nuclei, main ingredients are wave functions of bound and continuum nucleons, and a transition current operator. Detailed descriptions are given in our previous papers [26–29], which satisfactorily described the QE ν–A scattering [26,27] as well as the electron–nucleus scattering [28,29].

For obtaining the nucleon bound state wave functions, the Dirac equation is solved in the presence of the strong vector and scalar potentials based on σ–ω model [30]. The wave functions of the continuum nucleons are the solution of the Dirac equation with a relativistic phenomenological optical potential generated by Ohio State University group [31]. Note that we do not include the Coulomb distortion effect of an final electron (positron) in the CC reaction because the effect is within a few %.

We choose the nucleus fixed frame where target nucleus is seated at the origin of the coordinate system. Four-momenta of incident and outgoing $\nu(\bar{\nu})$ are labelled $p_i^\mu = (E_i, \mathbf{p}_i)$, $p_f^\mu = (E_f, \mathbf{p}_f)$. p_A^μ, p_{A-1}^μ, and p^μ represent four-momenta of target nucleus, residual nucleus, and final nucleon, respectively. In the laboratory frame, the differential cross section is given by the contraction between the lepton tensor and the hadron tensor [26]

$$\frac{d\sigma}{dT_p} = 4\pi^2 \frac{M_N M_{A-1}}{(2\pi)^3 M_A} \int \sin\theta_l \, d\theta_l \int \sin\theta_p \, d\theta_p \, p f_{\mathrm{rec}}^{-1} \times \sigma_M^Z [v_L R_L + v_T R_T + h v_T' R_T'], \tag{3}$$

where M_N is the nucleon mass, θ_l denotes the scattering angle of the lepton, and $h = -1$ ($h = +1$) corresponds to the helicity of the incident $\nu(\bar{\nu})$. θ_p and T_p represent the polar angle and the kinetic energy of the knocked-out nucleons, respectively. For the NC reaction, σ_M^Z is defined by

$$\sigma_M^Z = \left(\frac{G_F \cos(\theta_l/2) E_f M_Z^2}{\sqrt{2}\pi (Q^2 + M_Z^2)} \right), \tag{4}$$

and for the CC reaction,

$$\sigma_M^{W^\pm} = \sqrt{1 - \frac{M_l^2}{E_f}} \left(\frac{G_F \cos(\theta_C) E_f M_W^2}{2\pi (Q^2 + M_W^2)} \right)^2, \tag{5}$$

where G_F is the Fermi constant given by $G_F \simeq 1.16639 \times 10^{-11}$ MeV^{-2}, and M_Z (M_W) is the rest mass of Z (W)-boson. θ_C denotes the Cabibbo angle given by $\cos^2\theta_C \simeq 0.9749$. Detailed forms for recoil factor f_{rec}, kinematical coefficients v, and the corresponding response functions R are given in our previous paper for ν–A scattering in Ref. [26].

The nucleon current J represents the Fourier transform of the nucleon current density written as

$$J^{\mu} = \int \bar{\psi}_p \hat{\mathbf{J}}^{\mu} \psi_b e^{i\mathbf{q}\cdot\mathbf{r}} \, d^3 r, \tag{6}$$

where $\hat{\mathbf{J}}^{\mu}$ is a free nucleon current operator, and ψ_p and ψ_b are the wave functions of the knocked-out and the bound state nucleons, respectively. Total cross section is given as the integration of Eq. (3) in terms of the kinetic energy of the knocked-out nucleon:

$$\sigma = \int \frac{d\sigma}{dT_p} dT_p. \tag{7}$$

4. Results

In Figs. 1–3, we show total cross sections for the one-step process of the NC and CC reactions in terms of the incident $\nu(\bar{\nu})$ energy. Our one-step processes of the CC reactions, $^{12}\mathrm{C}(\nu_e, e^- p)^{11}\mathrm{C}$ and $^{12}\mathrm{C}(\bar{\nu}_e, e^+ n)^{11}\mathrm{B}$, are calculated by integrating the kinetic energy and summing all the possible states of knocked-out nucleon for the coincident $^{12}\mathrm{C}(\nu_e, e^- p)$ and $^{12}\mathrm{C}(\bar{\nu}_e, e^+ n)$ reactions, respectively. The $^{12}\mathrm{C}(\nu, \nu' p)^{11}\mathrm{B}$ and $^{12}\mathrm{C}(\nu, \nu' n)^{11}\mathrm{C}$ for the NC reaction are also given by the same way for the coincident $^{12}\mathrm{C}(\nu, \nu' p)$ and $^{12}\mathrm{C}(\nu, \nu' n)$ reactions, respectively. The ground states of $^{11}\mathrm{C}$ and $^{11}\mathrm{B}$ are taken as final nuclei with all summation of possible knocked-out nucleon states. Since the threshold energy for liberating a nucleon depends on the binding energy of the nucleon inside nucleus, they are presented from $E_\nu = 20$ MeV. Emitting muon in the CC reaction is energetically forbidden on the energy region considered here.

Our results are separately presented with the phenomenological optical potential (solid lines) for including the FSI of the outgoing nucleon with residual nuclei and without the potential (dotted lines). Since our calculations are obtained by explicitly integrating the coincident reactions $^{12}\mathrm{C}(\nu, \nu' N)$, $^{12}\mathrm{C}(\nu_e, e^- p)$, and $^{12}\mathrm{C}(\bar{\nu}_e, e^+ n)$, the optical potential used in each coincident reaction has a flux loss attributed to the inelastic channels. The effect of the FSI reduces the cross sections by a factor of 2. This reduction also appears to be on other calculations [27,32]. Note that the FSI affects the whole energy region.

Results of the two-step process, which are symbolized as data points in the figures, are taken from Ref. [2]. The first stage, the formation of compound nuclei, is calculated by the SM based on two different Hamiltonian, SFO and PSDMK2 [4]. For the second stage which is the decay processes, the HF statistical model description of various decay channels is exploited, where the FSI is introduced through the imaginary part of the optical potential in the phase shift of the particle transmission coefficients [4,33,34]. The cross sections of the one-step processes including the FSI are smaller than those of the SM + HF calculations by a factor of $2 \sim 3$ for $^{12}\mathrm{C}(\nu, \nu' p)^{11}\mathrm{B} + ^{12}\mathrm{C}(\nu, \nu' n)^{11}\mathrm{C}$ and $^{12}\mathrm{C}(\bar{\nu}_e, e^+ n)^{11}\mathrm{B}$. For $^{12}\mathrm{C}(\nu_e, e^- p)^{11}\mathrm{C}$ our results are less than those of the SM + HF by the amount of a factor of $3 \sim 4$. Consequently, the contributions by the one-step processes to the relevant nuclear abundances are smaller by a factor $2 \sim 4$ than those by the two-step processes.

Moreover, if we recall that the parameters in the optical potential for the HF description are mainly focused on the low energy region of the outgoing particles [34], more careful analysis for the tens of MeV energy region might be necessary because the FSI could suppress the cross sections on the whole $\nu(\bar{\nu})$ energy spectrum. As shown in the figures, the reduction of cross sections by the optical potential in the one-step processes may support such a conjecture.

Therefore, the FSI of an outgoing nucleon could be one of important ingredients even in the two-step process through whole energy region. In this context, the relatively small contribution of the one-step process in the figures might be comparable to those

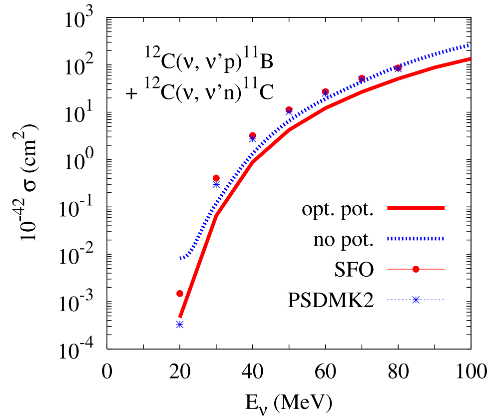

Fig. 1. (Color online.) The NC reaction by one-step processes, $^{12}\mathrm{C}(\nu, \nu' p)^{11}\mathrm{B} + {}^{12}\mathrm{C}(\nu, \nu' n)^{11}\mathrm{C}$, obtained by integrating the kinetic energy and summing all possible knocked-out nucleon states for $^{12}\mathrm{C}(\nu, \nu' N)$ reaction [26]. Data points for two-step processes, which are a sum of two cross sections, $^{12}\mathrm{C}(\nu, \nu')^{12}\mathrm{C}^* \to {}^{11}\mathrm{B} + p$ and $^{11}\mathrm{C} + n$, come from the SM and the HF statistical calculation for a branching ratio into final states [2]. SFO and PSDMK2 mean two different Hamiltonian exploited in the calculation.

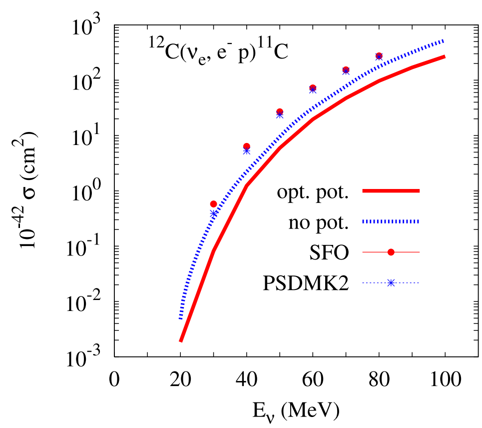

Fig. 2. (Color online.) The CC reaction for ν_e by one-step processes, $^{12}\mathrm{C}(\nu_e, e^- p)^{11}\mathrm{C}$, obtained by integrating the kinetic energy and summing all possible knocked-out proton states in the reaction, $^{12}\mathrm{C}(\nu_e, e^- p)$. Data points for two-step processes come from the SM and the HF calculation for $^{12}\mathrm{C}(\nu_e, e^-) \to {}^{12}\mathrm{N}^* \to {}^{11}\mathrm{C} + p$ [2]. Others are same as Fig. 1.

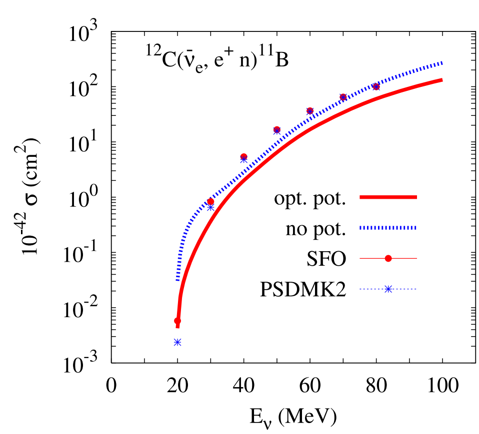

Fig. 3. (Color online.) The CC reaction for $\bar{\nu}_e$ by one-step processes, $^{12}\mathrm{C}(\bar{\nu}_e, e^+ n)^{11}\mathrm{B}$, obtained by integrating the kinetic energy and summing all possible bound neutron states in the reaction, $^{12}\mathrm{C}(\bar{\nu}_e, e^+ n)$. Data points for two-step processes come from the SM and the HF calculation for $^{12}\mathrm{C}(\bar{\nu}_e, e^+) \to {}^{12}\mathrm{B}^* \to {}^{11}\mathrm{B} + n$ [2]. Others are same as Fig. 1.

of the two-step process if the FSI effects could be deliberately taken into account in the two-step process.

5. Summary and conclusion

We estimate the contributions from the one-step process to the formation of ^{11}C and ^{11}B by the ν-process in the energy region beyond nucleon threshold. It corresponds to the contribution by a low energy tail of the QE peak. The contribution of the one-step process turns out to be important even in low energy region although it is smaller by a factor $3 \sim 4$ comparing with the two-step process. The process could be sensitive to the FSI between residual nuclei and outgoing nucleon.

Therefore, since most of nuclear models such as SM, RPA, and QRPA models consider only discrete or giant resonance states and do not explicitly takes the continuum states into account, it is necessary to additionally take the contribution of the one-step processes in the QE region.

The CRPA can describe both one- and two-step processes in a framework because it may include the continuum states in the QE region. But one could not separate explicitly the contributions due to the continuum states in the QE region. Here we explicitly show that the QE contributions could work for the nuclear abundances and the effect might be sensitive to how to take the FSI into account.

Unfortunately, there are still no data for the one-step process because it is a very challenging task to coincidentally detect final lepton and outgoing nucleons. Even in the two-step process one has only a few data for the first stage. More relevant data are necessary to pin down the ambiguities related to ν–A scattering in the nucleosynthesis. As for nuclear abundances, detailed studies of cross sections by the one-step process to the given temperature and their effects on the abundances in a network calculation of nucleosynthesis are in progress.

Acknowledgements

This work was supported by the Korea Science and Engineering Foundation (KOSEF) Grant funded by the Korean Government (MOST) (R01-2007-000-20569) and the Soongsil University Research Fund. Cheoun is greatly indebted for discussions with T. Kajino, T. Yoshida and T. Suzuki, and the hospitality of NAOJ, Japan.

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